III. WETTED SURFACE AREA AND METHOD CALCULATIONS

A. DETERMINATION OF THE WETTED SURFACE AREA

The wetted surface area of the SLICE hull was
calculated from the Lockheed ship drawings P1-100-01 dated
13 December 1994. The waterline used was 14 feet (Lockheed,
1994). For calculation of the wetted surface area the hull
was cut into numerous sections for easier analysis. Figures
3.1 through 3.4 show how the submerged hull was subdivided.
Where separate calculated surface areas overlapped,
appropriate area values were subtracted form the total.

1. Wetted Surface Area One

Wetted surface area One consisted of the forward angled
piece delineated in Figure 3.1 and was calculated using
triangular geometry. The calculations are provided in
Appendix A. The vertical depths were taken from the ship
drawings (Lockheed, 1994) and the horizontal distances from
the strut centerline for each station were calculated by
geometry. The shortened surface chord length from stations
0 to 3, due to the intersection with the wing part of the
strut, was accounted for by decreasing the horizontal
distance from the centerline. The angle between centerline
and surface intersection with DWL was constant at 8.1
degrees. The Simpson Rule was used to calculate the wetted
surface area of one side of one piece by connecting the
surface chords. Therefore, the total wetted surface area of
the two forward angled pieces was four times the calculated

area of one side. To ensure accuracy, a trapezoidal rule
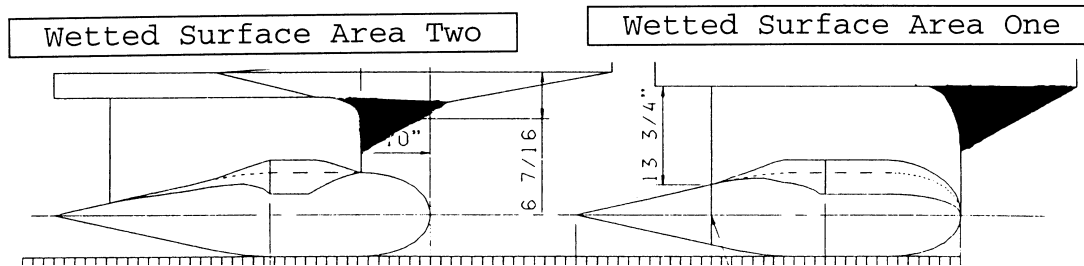calculation was also done.

Figure 3.1. Wetted Surface Areas One and Two (Lockheed, 1994).

2.   Wetted Surface Area Two

Wetted surface area Two consisted of the aft angled
piece, delineated in Figure 3.1. The same procedure used to
find area One was used to find area Two and the calculations
are provided in Appendix A. Because the aft connections are
different from the forward connections, the areas for the
forward pods and the aft pods are distinct.

3.   Wetted Surface Area Three

Area Three is the segment of the forward strut portion
which is wing shaped as shown in Figure 3.2. It encompasses
the surface from the DWL to the fillet which connects the
strut to the pod. Depth measurements were taken off SHIP
drawings (Lockheed, 1994) and the Simpson Rule was used to
calculate surface area. To ensure accuracy, a trapezoidal
rule calculation was also done. Calculations are provided
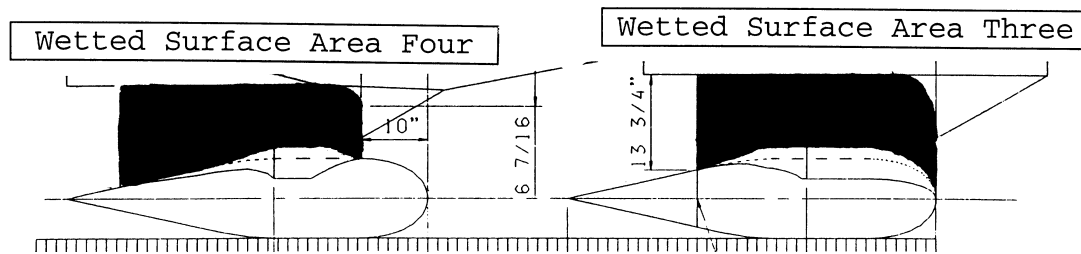in Appendix A.

Figure 3.2. Wetted Surface Areas Three and Four (Lockheed, 1994).

4.   Wetted Surface Area Four

Area Four is the segment of the aft strut portion which is wing shaped as shown in Figure 3.2. The same procedure used to find area Three was used to find area Four and the calculations are provided in Appendix A. Because the aft struts connect to the aft pods in a geometrically different way than the forward struts and pods, the fore and aft areas are different.

5.   Wetted Surface Area Five

Area Five is the forward fillet, outlined in Figure 3.3 and consists of that part of the wetted surface which attaches the forward struts to the forward pods. The ship drawings (Lockheed, 1994) provided measurements to the upper and lower coordinates at ship stations. Surface chord lengths between these two points were calculated and the Simpson Rule was used to calculate the surface area. To ensure accuracy, a trapezoidal rule calculation was also done. The calculations are provided in Appendix A.
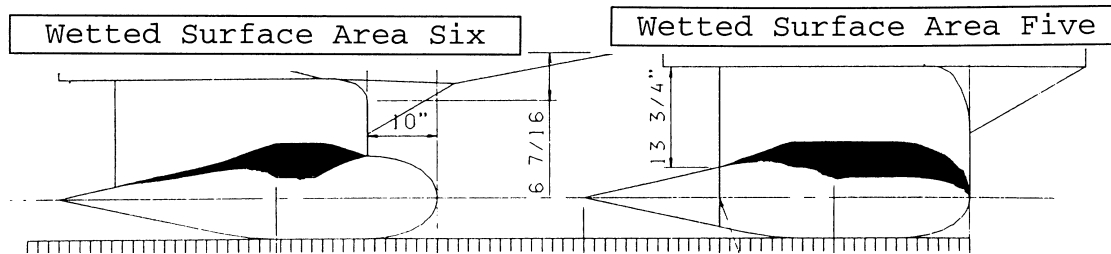
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Figure 3.3. Wetted Surface Areas Five and Six (Lockheed, 1994).

6.   Wetted Surface Area Six

Area Six is the aft fillet, outlined in Figure 3.3, corresponds to area Five of the forward hull. The surface was calculated the same way as the forward fillet but due to different for and aft connections, the areas for the forward segment and the aft segment are distinct. The calculations are provided in Appendix A.

7.   Wetted Surface Area Seven

Wetted surface area Seven is the forward pod, outlined in Figure 3.4. Using cylindrical geometry, circumferences were calculated at each station. At stations where the pods connected to the struts and fillets, an appropriate arc lengths was subtracted from the circumference. The Simpson Rule was used to calculate surface area and a trapezoidal rule was done as a check. As expected the Trapezoidal rule supplied a smaller value since the nose section's surface is curved between stations rather than flat. The calculations are provided in Appendix A.
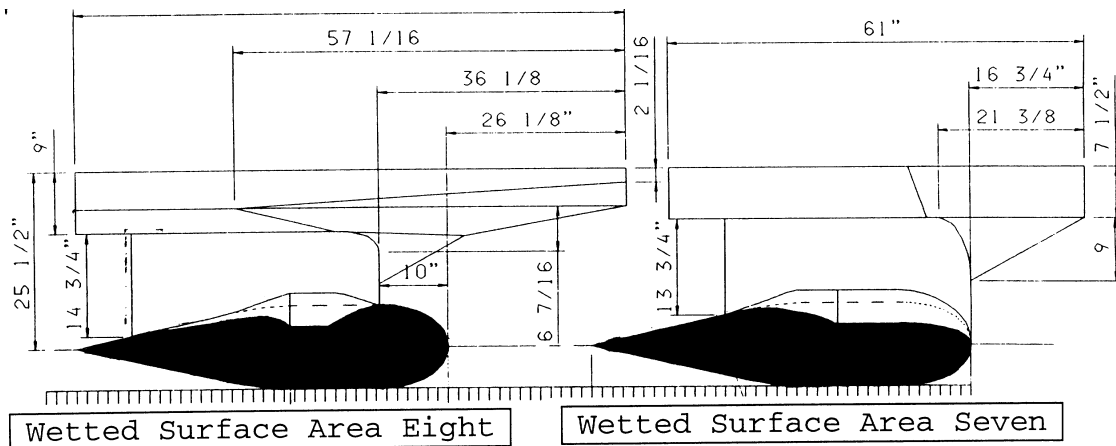
Figure 3.4. Wetted Surface Areas Seven and Eight (Lockheed, 1994).

8. Wetted Surface Area Eight

Figure 3.4 shows wetted surface area Eight which was calculated in the same manner as the forward pod. As before, the aft results differ form the forward ones because the aft connections are different from the forward connections. The calculations are provided in Appendix A.

B. ITTC PROCEDURE ON A SINGLE LENGTH

The model velocities V_M and model Froude Numbers Fn_M were taken from the Lockheed test tank data. (Lockheed, 1994) The desired range of ship velocities V_S was from 5 to 40 knots. By Froude scaling, the model Froude Number Fn_M is equal to the ship Froude Number Fn_S and with a scaling factor λ equal to 8, the model velocities were set by the following relationship.

$$V_M = \frac{V_S}{\sqrt{\lambda}} \qquad (22)$$

Lockheed ship drawings were used to establish a ship wetted surface area S_S as described in the wetted surface area calculation chapter and the model wetted surface area S_M was calculated by relating the ship wetted surface area and the scale factor λ appropriately.

$$S_M = \frac{S_S}{\lambda^2} \qquad (23)$$

The model total drag R_{T_M} provided by the Lockheed towing test, was the force required to move the model through the towing tank over the desired range of velocities. From the model total drag values, model total drag coefficients C_{T_M} were found. The test tank fluid density ρ_M was taken to be for fresh water at 68°F or 20°C.

$$\rho_M = \left(\frac{62.311}{32.174}\right)\frac{slugs}{ft^3} \qquad (24)$$

$$C_{T_M} = \frac{R_{T_M}}{\left(\frac{1}{2}\rho_M S_M V_M^2\right)} \qquad (25)$$

Equivalent model lengths $L_{M_{Equiv}}$ were calculated from the model Froude Numbers and model velocities where g is standard gravity. The twenty percent trim mean was taken as an average equivalent model length and used for all subsequent calculations.

$$g = 32.174 \frac{lb_m \cdot ft}{lb_f \cdot s^2} \qquad (26)$$

$$L_{M_{Equiv}} = \frac{V_M^2}{gFn_M^2} \qquad (27)$$

Reynolds Numbers were calculated based on the average equivalent model length and model velocities. These model Reynolds Numbers Rn_M have no true relation to the actual geometry of the model, they are only representations of flow over a flat plate of equivalent frictional length. The test tank fluid kinematic viscosity ν_M was taken to be for fresh water at 68°F or 20°C.

$$\nu_M = 1.08042 \times 10^{-5} \frac{ft^2}{s} \qquad (28)$$

$$Rn_M = \frac{V_M L_{M_{Equiv}}}{\nu_M} \qquad (29)$$

Using the ITTC equation, a value for the overall model frictional coefficient C_{F_M} was found and using this coefficient, a corresponding model frictional resistance R_{F_M} was calculated.

$$C_{F_M} = \frac{0.075}{\left(\log_{10} Rn_M - 2 \right)^2} \qquad (30)$$

$$R_{F_M} = C_{F_M} \left(\tfrac{1}{2} \rho_M S_M V_M^2 \right)$$

$$(31)$$

The model residual resistance coefficient C_{R_M} is what remains of the model total resistance coefficient once the model frictional resistance coefficient is subtracted from it. The residual resistance is mostly due to wave making resistance and these were considered equivalent. Since the model wave making resistance coefficient is Froude scaled, it is equal to the ship wave making coefficient C_{WM_S}.

$$C_{R_M} = \left(C_{T_M} - C_{F_M} \right) = C_{WM_M} = C_{WM_S} \qquad (32)$$

The model residual resistance R_{R_M}, equivalent to the model wave making resistance R_{WM_M}, was calculated from the model residual resistance coefficient.

$$R_{R_M} = C_{R_M} \left(\tfrac{1}{2} \, \rho_M S_M V_M^2 \right) = R_{WM_M} \qquad (33)$$

For the ship calculations, the ship velocities V_S and an equivalent ship length $L_{S_{Equiv}}$ were calculated using Froude scale factor relationships. Again by Froude similarity, the ship Froude Number matches the model Froude Number for corresponding speeds.

$$V_S = \sqrt{\lambda} \, V_M \qquad (34)$$

$$L_{S_{Equiv}} = \lambda \, L_{M_{Equiv}} \qquad (35)$$

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Using the ship velocities and the equivalent ship length, equivalent ship Reynolds Numbers Rn_S were found and used to calculate ship frictional resistance coefficients C_{F_S}. A corresponding value of the ship frictional resistance R_{F_S} was found. The test tank fluid kinematic viscosity ν_M and fluid density ρ_M are for sea water at 59°F or 15°C. This is the standardized temperature for ship resistance calculations (SNAME, 1988).

$$\nu_S = 1.27908 \times 10^{-5} \, \frac{ft^2}{s} \tag{36}$$

$$\rho_S = \left(\frac{64.042}{32.174}\right) \frac{slugs}{ft^3} \tag{37}$$

$$Rn_S = \frac{V_S L_{S_{Equiv}}}{\nu_S} \tag{38}$$

$$C_{F_S} = \frac{0.075}{\left(\log_{10} Rn_S - 2\right)^2} \tag{39}$$

$$R_{F_S} = C_{F_S}\left(\tfrac{1}{2}\rho_S S_S V_S^2\right) \tag{40}$$

Since the SLICE hull is similar to the SWATH hull, a correlation allowance of 0.0005 was used. Based on research this value is most appropriate for SWATH vessels (Kennell, 1992). It is noted that Lockheed also used a correlation allowance of 0.0005 in their analysis (Lockheed, 1994). By Froude scaling, the ship wave making resistance

coefficient C_{WM_S} equals the model wave making resistance coefficient at corresponding velocities. Therefore, the ship total resistance coefficient C_{T_S} was found and using this coefficient, a ship total resistance R_{T_S} was resolved.

$$C_{T_S} = C_{F_S} + C_{WM_S} + C_A \qquad (41)$$

$$R_{T_S} = C_{T_S} \left(\tfrac{1}{2} \rho_S S_S V_S^2 \right) \qquad (42)$$

The ship residual resistance coefficient was the remainder of the model total resistance coefficient once the ship frictional resistance and allowance coefficient were subtracted from it. As with the model, the residual resistance was analogous to the wave making resistance. A residual resistance was also calculated.

$$C_{R_S} = \left(C_{T_S} - C_{F_S} - C_A \right) = C_{WM_S} \qquad (43)$$

$$R_{R_S} = C_{R_S} \left(\tfrac{1}{2} \rho_S S_S V_S^2 \right) \qquad (44)$$

C.   ITTC PROCEDURE ON A SECTIONALIZED HULL

The same values for model velocities V_M, model Froude Numbers Fn_M, scaling factor λ, model wetted surface area S_M, model total drag R_{T_M}, and model total drag coefficients C_{T_M} were used. As in the previous analysis, the test tank fluid

density ρ_M and fluid kinematic viscosity ν_M were taken to be for fresh water at 68°F or 20°C.

Ship lengths L_S for each pod and strut section were taken from the ship drawings (Lockheed, 1994) and the proportional model lengths L_M were found. Then, Reynolds Numbers were calculated for each of the model sections. These model Reynolds Numbers Rn_M represent values for flow over a flat plate of equivalent frictional length.

$$Rn_M = \frac{V_M L_M}{\nu_M} \tag{45}$$

Using the ITTC equation, a value for the section's model frictional coefficient C_{F_M} was found.

$$C_{F_M} = \frac{0.075}{\left(\log_{10} Rn_M - 2\right)^2} \tag{46}$$

From the ITTC model frictional coefficients, corresponding model frictional resistances R_{F_M} were calculated for each section and then summed together to form an overall model frictional resistance.

$$R_{F_M} = C_{F_M} \left(\tfrac{1}{2} \rho_M S_M V_M^2 \right) \tag{47}$$

$$R_{F_M} = \sum_{i=1}^{n} R_{F_{M_i}} \qquad n = number \ of \ sections \tag{48}$$

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Once an overall frictional resistance was found, an equivalent frictional resistance coefficient $C_{F_{M_{Equiv}}}$ was found and from that an equivalent Reynolds Number $Rn_{M_{Equiv}}$ and equivalent length $L_{M_{Equiv}}$ were calculated.

$$C_{F_{M_{Equiv}}} = \frac{R_{F_M}}{\left(\frac{1}{2}\rho_M S_M V_M^2\right)} \tag{49}$$

$$Rn_{M_{Equiv}} = 10^{\left(2+\sqrt{\frac{0.075}{C_{F_{M_{Equiv}}}}}\right)} \tag{50}$$

$$L_{M_{Equiv}} = \frac{Rn_{M_{Equiv}}\nu_M}{V_M} \tag{51}$$

The model residual resistance coefficient C_{R_M} is what remains of the model total resistance coefficient once the model frictional resistance coefficient is subtracted from it. The residual resistance is mostly due to wave making resistance and these were considered equivalent. Since the model wave making resistance coefficient C_{WM_M} is Froude scaled, it is equal to the ship wave making coefficient C_{WM_S}.

$$C_{R_M} = \left(C_{T_M} - C_{F_M}\right) = C_{WM_M} = C_{WM_M} \tag{52}$$

The model residual resistance R_{R_M}, equivalent to the model wave making resistance R_{WM_M}, was calculated from the model residual resistance coefficient.

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$$R_{R_M} = C_{R_M}\left(\tfrac{1}{2}\rho_M S_M V_M^2\right) = R_{WM_M} \qquad (53)$$

The same ship velocities V_S, ship Froude Numbers Fn_S and ship wetted surface area S_S for the ITTC method were used in these calculations. As before, the ship fluid density ρ_S and fluid kinematic viscosity ν_S were taken to be for sea water at 59°F or 15°C.

Ship lengths L_S for each pod and strut section were taken from the ship drawings (Lockheed, 1994) and used to calculate Reynolds Numbers. These ship Reynolds Numbers Rn_S represent values for flow over a flat plate of equivalent frictional length.

$$Rn_S = \frac{V_S L_S}{\nu_S} \qquad (54)$$

Using the ITTC equation, a value for the ship section's frictional coefficient C_{F_S} was found.

$$C_{F_S} = \frac{0.075}{\left(\log_{10} Rn_S - 2\right)^2} \qquad (55)$$

From the ship section's ITTC frictional coefficients, corresponding ship frictional resistances R_{F_S} were calculated for each section and these were summed together to form an overall ship frictional resistance.

$$R_{F_S} = C_{F_S}\left(\tfrac{1}{2}\rho_S S_S V_S^2\right) \qquad (56)$$

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$$R_{F_S} = \sum_{i=1}^{n} R_{F_{S_i}} \qquad n = number\ of\ sec tions \qquad (57)$$

Once an overall frictional resistance was found, an equivalent ship frictional resistance coefficient $C_{F_{S_{Equiv}}}$ was found and from that an equivalent ship Reynolds Number $Rn_{S_{Equiv}}$ and equivalent ship length $L_{S_{Equiv}}$ were calculated.

$$C_{F_{S_{Equiv}}} = \frac{R_{F_S}}{\left(\frac{1}{2}\, \rho_S S_S V_S^2\right)} \qquad (58)$$

$$Rn_{S_{Equiv}} = 10^{\left(2 + \sqrt{\frac{0.075}{C_{F_{S_{Equiv}}}}}\right)} \qquad (59)$$

$$L_{S_{Equiv}} = \frac{Rn_{S_{Equiv}}\, \nu_S}{V_S} \qquad (60)$$

The correlation allowance C_A was taken to be 0.0005, and the ship wave making resistance coefficient C_{WM_S} was taken to be equal to the model wave making resistance coefficient at corresponding velocities. Therefore, the ship total resistance coefficient C_{T_S} was found and using this coefficient, a ship total resistance R_{T_S} was resolved.

$$C_{T_S} = C_{F_{S_{Equiv}}} + C_{WM_S} + C_A \qquad (61)$$

$$R_{T_S} = C_{T_S}\left(\frac{1}{2}\, \rho_S S_S V_S^2\right) \qquad (62)$$

The ship residual resistance coefficient was the remainder of the model total resistance coefficient once the ship frictional resistance and allowance coefficients were subtracted from it. As with the model, the residual resistance was analogous to the wave making resistance. A residual resistance was also calculated.

$$C_{R_S} = \left(C_{T_S} - C_{F_S} - C_A\right) = C_{WM_S} \tag{63}$$

$$R_{R_S} = C_{R_S}\left(\tfrac{1}{2}\,\rho_S S_S V_S^2\right) \tag{64}$$

D. HUGHES PROCEDURE ON A SECTIONALIZED HULL

The values for model velocities V_M, model Froude Numbers Fn_M, scaling factor λ, model wetted surface area S_M, model total drag R_{T_M}, and model total drag coefficients C_{T_M} were the same as in previous analyses. Again, the test tank fluid density ρ_M and fluid kinematic viscosity ν_M were taken to be for fresh water at 68°F or 20°C.

Ship lengths L_S for each pod and strut section were taken from the ship drawings (Lockheed, 1994) and the proportional model lengths L_M were found. Then, Reynolds Numbers were calculated for each model section. These model Reynolds Numbers Rn_M represent values for flow over a flat plate of equivalent frictional length.

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$$Rn_M = \frac{V_M L_M}{\nu_M} \tag{65}$$

Using the Hughes equation, a value for each section's model frictional coefficient C_{FO_M} was found.

$$C_{FO_M} = \frac{0.066}{\left(\log_{10} Rn_M - 2.03\right)^2} \tag{66}$$

From the Hughes model frictional coefficients, corresponding model frictional resistances R_{FO_M} were calculated for each section and then summed together to form an overall model frictional resistance.

$$R_{FO_M} = C_{FO_M}\left(\tfrac{1}{2}\rho_M S_M V_M^2\right) \tag{67}$$

$$R_{FO_M} = \sum_{i=1}^{n} R_{FO_{M_i}} \qquad n = number\ of\ sections \tag{68}$$

Once an overall frictional resistance was found, an equivalent model frictional resistance coefficient $C_{FO_{M\,Equiv}}$ was found and from that an equivalent model Reynolds Number $Rn_{M_{Equiv}}$ and equivalent model length $L_{M_{Equiv}}$ were calculated.

$$C_{FO_{M\,Equiv}} = \frac{R_{FO_M}}{\left(\tfrac{1}{2}\rho_M S_M V_M^2\right)} \tag{69}$$

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$$Rn_{M_{Equiv}} = 10^{\left(2.03+\sqrt{\frac{0.066}{C_{FO_{M_{Equiv}}}}}\right)} \tag{70}$$

$$L_{M_{Equiv}} = \frac{Rn_{M_{Equiv}}\,\nu_M}{V_M} \tag{71}$$

As explained in Chapter II, the form factor r was found by raising the Hughes curve up to the model total resistace coefficient at a low speed. Figure 2.3 shows the new curve which is the product of multiplying the form factor and the Hughes equivalent resistance coefficients The new curve is the sum of the model equivalent frictional resistance coefficient and the model form drag coefficient. From this, the model form drag coefficient C_{FORM_M} and the model form drag R_{FORM_M} were found.

$$C_{FORM_M} = C_{FO_M}(r-1) \tag{72}$$

$$R_{FORM_M} = C_{FORM_M}\left(\tfrac{1}{2}\,\rho_M S_M V_M^2\right) \tag{73}$$

The model wave making C_{WM_M} is what remains of the model total resistance coefficient once the model frictional resistance coefficient and model form drag coefficient are subtracted from it. Since the model wave making resistance coefficient is Froude scaled, it is equal to the ship wave making coefficient C_{WM_S}.

$$C_{WM_M} = \left(C_{T_M} - C_{FO_M} - C_{FORM_M}\right) = \left(C_{T_M} - r\,C_{FO_M}\right) = C_{WM_S} \tag{74}$$

The model residual resistance R_{R_M}, equivalent to the model wave making resistance R_{WM_M}, was calculated from the model residual resistance coefficient by the relation:

$$R_{R_M} = C_{R_M}\left(\tfrac{1}{2}\,\rho_M S_M V_M^2\right) = R_{WM_M} \tag{75}$$

The same ship velocities V_S, ship Froude Numbers Fn_S and ship wetted surface area S_S for the ITTC method were used in these calculations. As before, the ship fluid density ρ_S and fluid kinematic viscosity ν_S were taken to be for sea water at 59°F or 15°C.

Ship lengths L_S for each pod and strut section were taken from the ship drawings (Lockheed, 1994) and used to calculate Reynolds Numbers. These ship Reynolds Numbers Rn_S represent values for flow over a flat plate of equivalent frictional length.

$$Rn_S = \frac{V_S L_S}{\nu_S} \tag{76}$$

Using the Hughes equation, a value for the ship frictional coefficient C_{FO_S} was found for each section.

$$C_{FO_S} = \frac{0.066}{\left(\log_{10} Rn_S - 2.03\right)^2} \tag{77}$$

From the ship Hughes frictional coefficients, corresponding ship frictional resistances R_{FO_S} were

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calculated for each section and then summed together to form an overall ship frictional resistance.

$$R_{FO_S} = C_{FO_S} \left(\tfrac{1}{2} \, \rho_S S_S V_S^2 \right) \tag{78}$$

$$R_{FO_S} = \sum_{i=1}^{n} R_{FO_{S_i}} \qquad n = number \; of \; \sec tions \tag{79}$$

Once an overall frictional resistance was found, an equivalent ship frictional resistance coefficient $C_{FO_{S_{Equiv}}}$ was found and from that an equivalent ship Reynolds Number $Rn_{S_{Equiv}}$ and equivalent ship length $L_{S_{Equiv}}$ were calculated.

$$C_{FO_{S_{Equiv}}} = \frac{R_{FO_S}}{\left(\tfrac{1}{2} \, \rho_S S_S V_S^2 \right)} \tag{80}$$

$$Rn_{S_{Equiv}} = 10^{\left(2 + \sqrt{\frac{0.075}{C_{FO_{S_{Equiv}}}}} \right)} \tag{81}$$

$$L_{S_{Equiv}} = \frac{Rn_{S_{Equiv}} \, \nu_S}{V_S} \tag{82}$$

Multiplying the ship equivalent frictional resistance coefficients by the established form factor r yields a new curve which is the sum of the ship equivalent frictional resistance coefficient and the ship form drag coefficient. Therefore the ship form drag coefficient C_{FORM_S} and the ship form drag R_{FORM_S} can be found.

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$$C_{FORM_S} = C_{FO_S}(r-1) \tag{83}$$

$$R_{FORM_S} = C_{FORM_S}\left(\tfrac{1}{2}\,\rho_S S_S V_S^2\right) \tag{84}$$

The correlation allowance C_A was taken to be 0.0005, and the ship wave making resistance coefficient C_{WM_S} was taken to be equal to the model wave making resistance coefficient at corresponding velocities. Therefore, the ship total resistance coefficient C_{T_S} was found and using this coefficient, a ship total resistance R_{T_S} was resolved.

$$C_{T_S} = \left(C_{FO_{S\,Equiv}} + C_{FORM_S} + C_{WM_S} + C_A\right) \tag{85}$$

$$R_{T_S} = C_{T_S}\left(\tfrac{1}{2}\,\rho_S S_S V_S^2\right) \tag{86}$$

The ship residual resistance coefficient C_{R_S} was the remainder of the model total resistance coefficient once the ship frictional resistance and allowance coefficients were subtracted from it. The residual resistance R_{R_S} includes the wave making effects and the form drag.

$$C_{R_S} = \left(C_{T_S} - C_{FO_S} - C_A\right) = \left(C_{WM_S} + C_{FORM_S}\right) \tag{87}$$

$$R_{R_S} = C_{R_S}\left(\tfrac{1}{2}\,\rho_S S_S V_S^2\right) \tag{88}$$

E.   MODIFIED HUGHES PROCEDURE ON A SECTIONALIZED HULL

For this analysis, the values for model velocities V_M, model Froude Numbers Fn_M, scaling factor λ, model wetted surface area S_M, model total drag R_{T_M}, and model total drag coefficients C_{T_M} were the same as used in the previous analyses. Again, the test tank fluid density ρ_M and fluid kinematic viscosity ν_M were taken to be for fresh water at 68°F or 20°C.

Ship lengths L_S for each pod and strut section were taken from the ship drawings (Lockheed, 1994) and the proportional model lengths L_M were found. Then, Reynolds Numbers were calculated for each model section. These model Reynolds Numbers Rn_M represent values for flow over a flat plate of equivalent frictional length.

$$Rn_M = \frac{V_M L_M}{\nu_M} \tag{89}$$

Using the Hughes equation, a value for each section's model frictional coefficient C_{FO_M} was found.

$$C_{FO_M} = \frac{0.066}{\left(\log_{10} Rn_M - 2.03\right)^2} \tag{90}$$

From the Hughes model frictional coefficients, corresponding model frictional resistances R_{FO_M} were calculated for each section and then summed together to form an overall model frictional resistance.

$$R_{FO_M} = C_{FO_M} \left(\tfrac{1}{2} \, \rho_M S_M V_M^2 \right) \tag{91}$$

$$R_{FO_M} = \sum_{i=1}^{n} R_{FO_{M_i}} \qquad n = number \ of \ sec tions \tag{92}$$

Once an overall frictional resistance was found, an equivalent model frictional resistance coefficient $C_{FO_{M\,Equiv}}$ was found and from that an equivalent model Reynolds Number $Rn_{M_{Equiv}}$ and equivalent model length $L_{M_{Equiv}}$ were calculated.

$$C_{FO_{M\,Equiv}} = \frac{R_{FO_M}}{\left(\tfrac{1}{2} \, \rho_M S_M V_M^2 \right)} \tag{93}$$

$$Rn_{M_{Equiv}} = 10^{\left(2.03 + \sqrt{\frac{0.066}{C_{FO_{M\,Equiv}}}} \right)} \tag{94}$$

$$L_{M_{Equiv}} = \frac{Rn_{M_{Equiv}} \, \nu_M}{V_M} \tag{95}$$

Here is the modification to the Hughes Method. Rather than consider it as a single term, the form drag was further subdivided into strut and pod components. By doing this, results from a separate analysis of the strut were incorporated into the model research. In particular, the struts were investigated as wing shapes whose form drag coefficient was a constant.

The wing chosen which most closely resembled the struts was NACA 0012-64. Using Figure 3.3, a wing drag coefficient $C_{d_{Wing}} = 0.0044$ was extracted. The wave making resistance of the strut was taken to be negligible at a low Froude Number. The Froude Number chosen was where the model total resistance coefficient was minimum at low speeds. For a Froude Number of $Fn = 0.2$, the model strut frictional resistance coefficient was $C_{FO_{Strut_M}} = 0.004120136$ and this was subtracted from the wing drag coefficient to determine the strut form drag coefficient $C_{FORM_{Strut}}$.

$$C_{Form_{Strut}} = C_{d_{Wing}} - C_{FO_{Strut_M}} = 0.000279864 \qquad (96)$$

The model strut form drag $R_{FORM_{Strut_M}}$ was found using the model strut wetted surface area S_{Strut_M}. The strut surface area was taken as the sum of wetted surface areas One, Two, Three, Four, Five, and Six.

$$R_{FORM_{Strut_M}} = C_{FORM_{Strut}} \left(\tfrac{1}{2} \rho_M S_{Strut_M} V_M^2 \right) \qquad (97)$$

Then the model frictional resistance and the model strut form drag were added together to find a single equivalent coefficient C_{Equiv_M} which could then be multiplied by the form factor r to raise the Hughes curve to the model total at low Froude Numbers.

$$C_{Equiv_M} = \frac{\left(R_{FO_M} + R_{FORM_{Strut_M}} \right)}{\left(\tfrac{1}{2} \rho_M S_M V_M^2 \right)} \qquad (98)$$

$$R_{Equiv_M} = C_{Equiv_M} \left(\tfrac{1}{2} \, \rho_M S_M V_M^2 \right)$$ (99)

The difference between the value multiplied by the form factor and the premultiplied value was set equal to the model pod form drag $R_{Form_{Pod_M}}$. The corresponding model pod from drag coefficient $C_{FORM_{Pod_M}}$ was calculated using the model pod wetted surface area S_{Pod_M}. The pod wetted surface area was taken as the sum of wetted surface areas Seven and Eight.

$$R_{Form_{Pod_M}} = (r - 1) \, R_{Equiv_M}$$ (100)

$$C_{FORM_{Pod_M}} = \frac{R_{FORM_{Pod_M}}}{\left(\tfrac{1}{2} \, \rho_M S_{Pod_M} V_M^2 \right)}$$ (101)

The total model form drag was the strut form drag plus the pod form drag and using the entire model wetted surface area a model form drag coefficient was calculated.

$$R_{FORM_M} = R_{FORM_{Strut_M}} + R_{FORM_{Pod_M}}$$ (102)

$$C_{FORM_M} = \frac{R_{FORM_M}}{\left(\tfrac{1}{2} \, \rho_M S_M V_M^2 \right)}$$ (103)

The model wave making C_{WM_M} was found by subtracting the model frictional resistance coefficient and model form drag coefficient from the model total resistance coefficient. Since the model wave making resistance coefficient is Froude

scaled, it is equal to the ship wave making coefficient C_{WM_S} at comparable speeds. Additionally, the model wave making resistance R_{WM_M}, was calculated.

$$C_{WM_M} = \left(C_{T_M} - C_{FO_{M_{Equiv}}} - C_{FORM_M} \right) = C_{WM_S} \qquad (104)$$

$$R_{WM_M} = C_{WM_M} \left(\tfrac{1}{2} \rho_M S_M V_M^2 \right) \qquad (105)$$

The model residual resistance coefficient C_{R_M} is what remains of the model total resistance coefficient once the equivalent model frictional resistance coefficient is subtracted from it. The model residual resistance R_{R_M} includes the wave making resistance and the form drag.

$$C_{R_M} = \left(C_{T_M} - C_{FO_{M_{Equiv}}} \right) = \left(C_{WM_M} + C_{FORM_M} \right) \qquad (106)$$

$$R_{R_M} = C_{R_M} \left(\tfrac{1}{2} \rho_M S_M V_M^2 \right) \qquad (107)$$

The same ship velocities V_S, ship Froude Numbers Fn_S and ship wetted surface area S_S for the ITTC method were used in these calculations. As before, the ship fluid density ρ_S and fluid kinematic viscosity ν_S were taken to be for sea water at 59°F or 15°C.

Ship lengths L_S for each pod and strut section were taken from the ship drawings (Lockheed, 1994) and used to calculate Reynolds Numbers. These ship Reynolds Numbers Rn_S

represent values for flow over a flat plate of equivalent frictional length.

$$Rn_S = \frac{V_S L_S}{\nu_S} \qquad (108)$$

Using the Hughes equation, a value for the ship frictional coefficient C_{FO_S} was found for each section.

$$C_{FO_S} = \frac{0.066}{\left(\log_{10} Rn_S - 2.03\right)^2} \qquad (109)$$

From the ship Hughes frictional coefficients, corresponding ship frictional resistances R_{FO_S} were calculated for each section and then summed together to form an overall ship frictional resistance.

$$R_{FO_S} = C_{FO_S}\left(\tfrac{1}{2}\,\rho_S S_S V_S^2\right) \qquad (110)$$

$$R_{FO_S} = \sum_{i=1}^{n} R_{FO_{S_i}} \qquad n = number\ of\ sec tions \qquad (111)$$

Once an overall frictional resistance was found, an equivalent ship frictional resistance coefficient $C_{FO_{S_{Equiv}}}$ was found and from that an equivalent ship Reynolds Number $Rn_{S_{Equiv}}$ and equivalent ship length $L_{S_{Equiv}}$ were calculated.

$$C_{FO_{S_{Equiv}}} = \frac{R_{FO_S}}{\left(\tfrac{1}{2}\,\rho_S S_S V_S^2\right)} \qquad (112)$$

$$Rn_{S_{Equiv}} = 10^{\left(2 + \sqrt{\frac{0.075}{C_{FOS_{Equiv}}}}\right)} \qquad (113)$$

$$L_{S_{Equiv}} = \frac{Rn_{S_{Equiv}} \nu_S}{V_S} \qquad (114)$$

Since the strut form drag coefficient $C_{FORM_{Strut}}$ was taken as constant, the ship strut form drag $R_{FORM_{Strut_S}}$ was found using the ship strut wetted surface area S_{Strut_S}.

$$R_{FORM_{Strut_S}} = C_{FORM_{Strut}} \left(\tfrac{1}{2} \rho_S S_{Strut_S} V_S^2\right) \qquad (115)$$

Then the ship frictional resistance and the ship strut form drag were added together to find a single equivalent coefficient C_{Equiv_S} which was multiplied by the form factor r to raise the Hughes curve.

$$C_{Equiv_S} = \frac{\left(R_{FO_S} + R_{FORM_{Strut_S}}\right)}{\left(\tfrac{1}{2} \rho_S S_S V_S^2\right)} \qquad (116)$$

$$R_{Equiv_S} = C_{Equiv_S} \left(\tfrac{1}{2} \rho_S S_S V_S^2\right) \qquad (117)$$

The difference between the value multiplied by the form factor and the premultiplied value was set equal to the ship pod form drag $R_{Form_{Pod_S}}$. The corresponding ship pod from drag

coefficient $C_{FORM_{Pod_S}}$ was calculated using the ship pod wetted surface area S_{Pod_S}.

$$R_{Form_{Pod_S}} = (r-1)\, R_{Equiv_S} \tag{118}$$

$$C_{FORM_{Pod_S}} = \frac{R_{FORM_{Pod_S}}}{\left(\frac{1}{2}\, \rho_S S_{Pod_S} V_S^2\right)} \tag{119}$$

The total ship form drag R_{FORM_S} was the strut form drag plus the pod form drag and using the entire ship wetted surface area, a ship form drag coefficient C_{FORM_S} was found.

$$R_{FORM_S} = R_{FORM_{Strut_S}} + R_{FORM_{Pod_S}} \tag{120}$$

$$C_{FORM_S} = \frac{R_{FORM_S}}{\left(\frac{1}{2}\, \rho_S S_S V_S^2\right)} \tag{121}$$

Since the wave making resistance coefficient is Froude scaled, the ship wave making resistance coefficient C_{WM_S} is equal to the model wave making coefficient C_{WM_M}. The corresponding ship wave making resistance R_{WM_S}, was then quantified.

$$C_{WM_S} = C_{WM_M} \tag{122}$$

$$R_{WM_S} = C_{WM_S}\left(\frac{1}{2}\, \rho_S S_S V_S^2\right) \tag{123}$$

With a correlation allowance C_A of 0.0005, the ship total resistance coefficient C_{T_S} was found and using this coefficient, the ship total resistance R_{T_S} was resolved.

$$C_{T_S} = \left(C_{FO_{S_{Equiv}}} + C_{FORM_S} + C_{WM_S} + C_A \right) \tag{124}$$

$$R_{T_S} = C_{T_S} \left(\tfrac{1}{2} \, \rho_S S_S V_S^2 \right) \tag{125}$$

The ship residual resistance coefficient C_{R_S} was the remainder of the model total resistance coefficient once the ship frictional resistance and allowance coefficients were subtracted from it. The residual resistance R_{R_S} includes the wave making effects and the form drag.

$$C_{R_S} = \left(C_{T_S} - C_{FO_{S_{Equiv}}} - C_A \right) = \left(C_{WM_S} + C_{FORM_S} \right) \tag{126}$$

$$R_{R_S} = C_{R_S} \left(\tfrac{1}{2} \, \rho_S S_S V_S^2 \right) \tag{127}$$